

A study of the influence of synchrotron radiation quantum fluctuations on the synchrotron oscillations of a single electron using undulator radiation

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Abstract

A single electron circulating in a storage ring is a very peculiar object. Synchrotron radiation quantum fluctuations cause stochastic processes in the synchrotron oscillation of an electron. The radiation from an undulator permits one to obtain discrete moments of the longitudinal electron motion. Experiments with a single electron on the VEPP-3 optical klystron are described.

1. Introduction

In a previous paper [1] we reported the results of the Brown–Twiss experiment with undulator radiation of a single electron circulating in a storage ring. It was found that the correlation length of photocounts is sufficiently less (actually, less than the time resolution of our equipment) than the “natural” bunch length caused by the quantum fluctuations of synchrotron radiation. The interpretation of this result is the following: the length of localization of the electron is sufficiently less than the natural bunchlength. It was also indicated that the longitudinal coordinate of the electron oscillates with the synchrotron frequency.

In this paper we describe the investigation of the single electron longitudinal motion.

2. The experimental set-up

The layout of our installation is shown in the Figs. 1 and 2. The electron circulates in the storage ring VEPP-3 with a revolution frequency $F_{\text{rev}} = 4.012$ MHz modulated by the frequency of synchrotron oscillations $\Omega/2\pi$ (about 1 kHz). The light emitted by the electron in the undulator is detected by the photomultiplier. The photocounts pulses pass through the discriminator–shaper. These pulses of a standard shape start the time-to-digital converter. The reference pulses phased with the storage ring RF system

coming with the revolution frequency stop the converter. So we measure the delay between the time when the electron enters to the undulator and the first reference pulse after this event. The average frequency of the photocounts (about 20 kHz) is less than the revolution frequency, therefore another circuit counts the number of revolution periods between the photocounts. The delay and the number of revolutions are written into the memory of the CAMAC controller. Thus the result of the measurements is a couple of arrays which comprises the dependence of delay on the revolution number. The small part of this dependence is shown in Fig. 3.

3. Preliminary data handling

To obtain more precise information about the electron dynamics, we have to exclude the errors from the experimental data. There are two sources of errors. First, uncorrelated photocounts, which are present even in the absence of an electron. Second, the jitter of pulses at the output of the discriminator–shaper caused by statistical fluctuations of the shape of the pulses from the photomultiplier. On the another hand, we know that the dependence of the longitudinal coordinate s of an electron on time t is sinusoidal with slowly varying amplitude A and phase ϕ :

$$s = ct + A(t) \sin(\Omega n/F_{\text{rev}} + \phi(t)), \quad (1)$$

where n is the revolution number, and c is speed of light.

Taking into account these circumstances we use the following algorithm of filtering the date sequence. We take the small part of the sequence with duration T (typically

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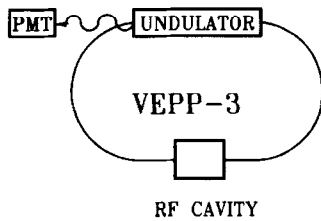


Fig. 1. Layout of the installation.

we choose T to be about a few periods of the synchrotron oscillations). Using the least-squares method we obtain the amplitude and the phase of the fitting sinusoid and the r.m.s. error. After that we exclude from the consideration all points with a deviation larger than two r.m.s. errors. We repeat this least square fitting twice more, excluding about

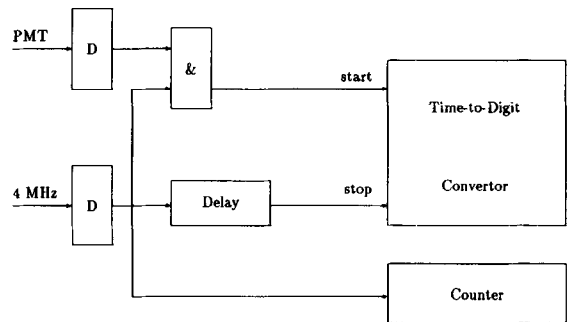


Fig. 2. Layout of the time interval measurement.

15% of experimental points and obtain a “clean” sequence (Fig. 4) with fitted amplitude and phase of oscillations.



Fig. 3. The small part of the measured dependence.

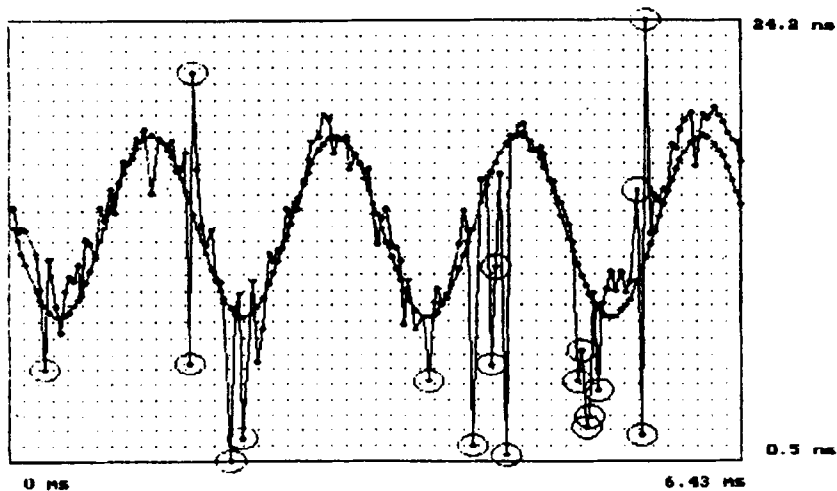


Fig. 4. The “clean” dependence.

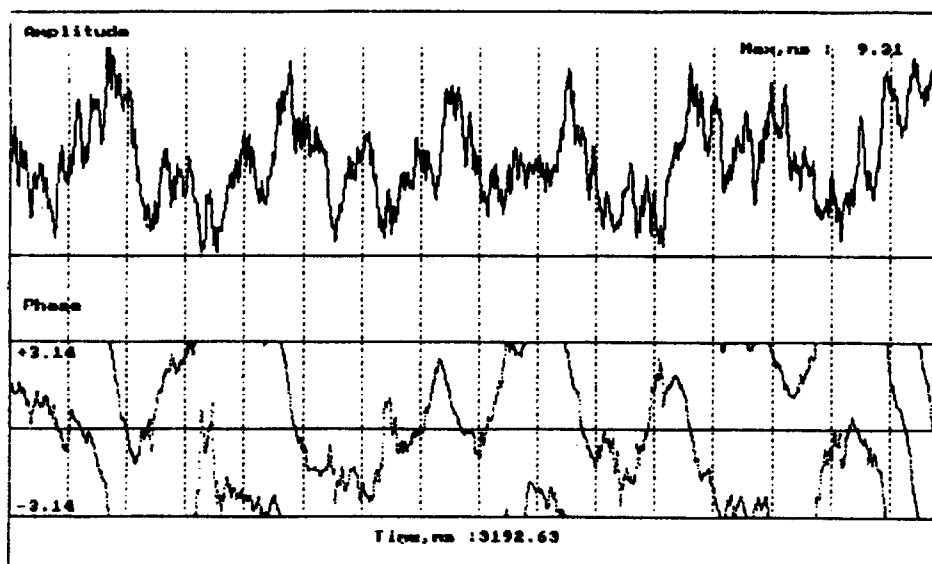


Fig. 5. Time dependence of amplitude and phase of synchrotron oscillations.

To estimate the “optimal” value of the partial sequence duration T we used the consideration of the optimal filter for a sequence [2]. The least-squares procedure is actually a kind of filters and T^{-1} is the width of the filter. One can easily obtain the estimation for the optimal value of T :

$$T_{\text{opt}} \approx \frac{\sigma}{A} \sqrt{\frac{\tau}{\nu}}, \quad (2)$$

where σ is the r.m.s. error, τ is the longitudinal damping time, and ν is the frequency of the photocounts. Actually we chose T to be few times larger than for the average amplitude. So, we lost in the resolution for large amplitudes, but decreased the noise dramatically for all amplitudes.

Applying such treatment to various partial sequences we obtain the time dependence of amplitude $A(t)$ and slow phase $\phi(t)$ depicted in Fig. 5. The electron trajectory in the polar coordinates A, ϕ is shown in Fig. 6.

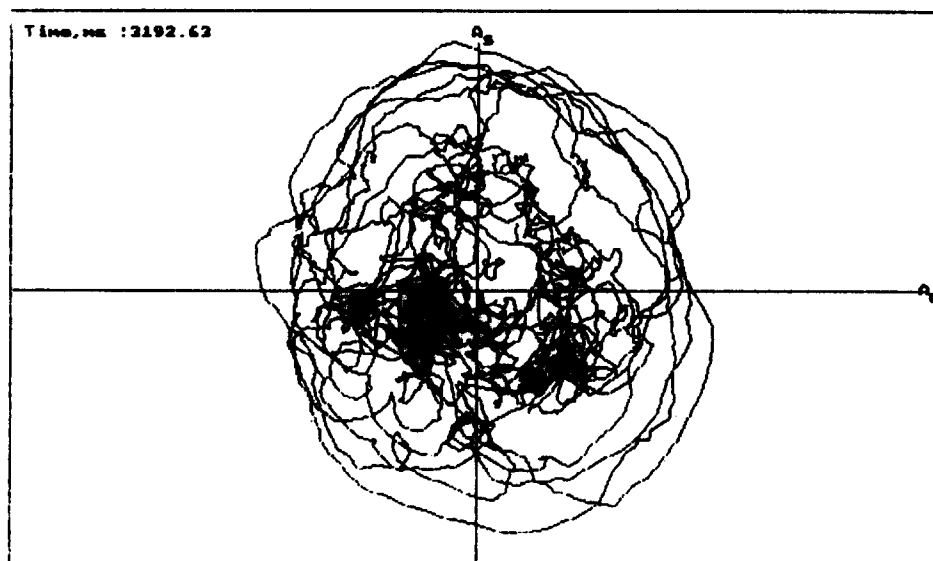


Fig. 6. Trajectory of synchrotron oscillations in phase coordinates.

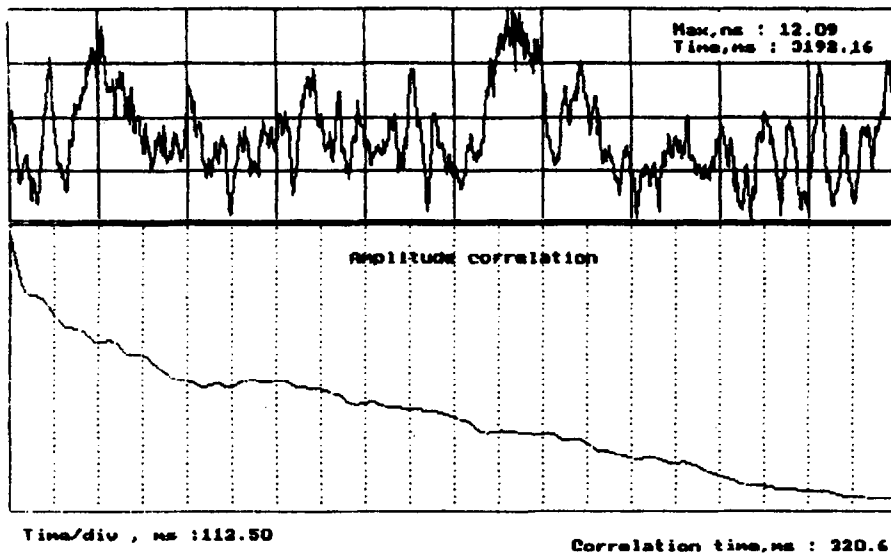


Fig. 7. The amplitude correlation function.

Let us discuss qualitatively some features of this trajectory. It looks continuous but non-differentiable. These properties are very natural for Brownian motion. This view of trajectory also indicates that our filtering algorithm provides a good suppression of noises (otherwise there would appear discontinuities) and has a rather broad band (otherwise the trajectory would be smooth). The motion is irregular except for large amplitudes where there is a regular rotation caused by the nonlinearity of the synchrotron oscillations. The trajectory fills more or less homogeneously the central part of the phase plane except for the close vicinity of the origin. This “small hole” in the phase space distribution may be caused by fluctuations of the RF voltage (see below).

4. The correlation functions

The correlation functions for amplitude and phase are shown in Figs. 7 and 8, respectively. The characteristic durations are very different (≈ 300 ms and ≈ 15 ms). Note that the correlation time for the amplitudes is almost equal to the damping time of the synchrotron oscillations. The short correlation time for the phase may also be caused by the fluctuations of the RF voltage.

5. Observations of two electrons

To separate the influence of the quantum fluctuations of radiation on the electron dynamics from the influence of

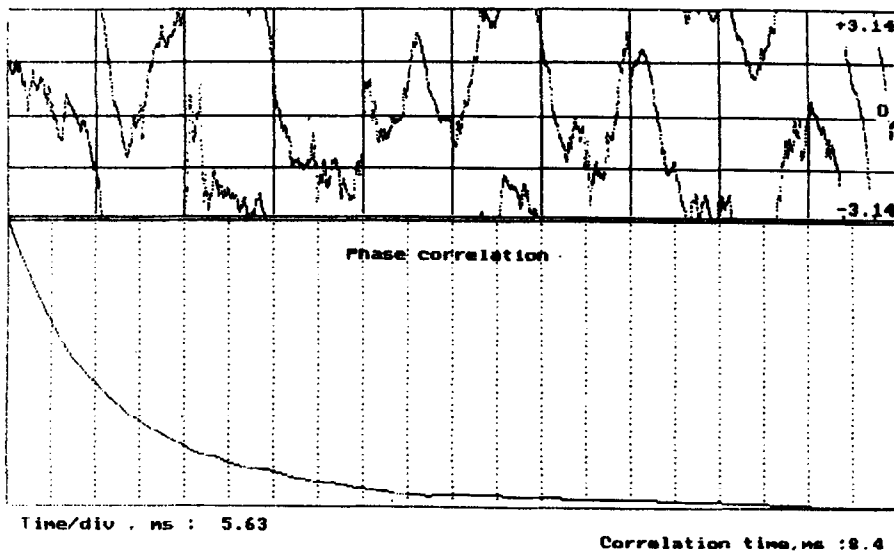


Fig. 8. The phase correlation function.

other noises we performed the same experiment with two electrons in the storage ring. The “kicks” of the photon emission for two electrons are obviously uncorrelated, but “kicks” from noise of the RF and magnetic systems are correlated. The handling of the photocounts data is more complicated now and demands the further investigations to be performed.

6. Conclusion

In the experiments described in this paper we demonstrated the stochastic behavior of the electron similar to the Brownian motion. However the phenomenon is sufficiently different from the last one as the temperature of the field

oscillators which interacts with the electron is equal to zero. In the reference system moving with the electron the effective temperature is proportional to its acceleration [3] and the interpretation becomes similar to the conventional consideration of thermal fluctuations.

References

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